

Over the Air Testing: Important Antenna Parameters, Testing Methodologies and Standards

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Abstract – Increasing use of higher frequencies and tighter integration of chipsets and antennas require increased focus on over the air (OTA) testing. While standard antenna testing, electromagnetic compatibility (EMC) testing or wireless communication in general are well established fields for a long time, many engineers from previously unrelated fields now require a firm understanding of OTA testing methodologies and key antenna parameters. This paper summarizes the most important antenna parameters, system calibration and test procedures for accurate and reliable OTA testing of components and devices in every stage of development.

I. INTRODUCTION

Whether in low cost devices targeting the IoT market, highly integrated radio frontends for satellite communication links, radar, or 5G New Radio mm-wave devices, integrated antennas become more common with each development cycle. Therefore, testing a device under test (DUT) over the air (OTA) becomes more useful or even mandatory to a broader audience. For conducting reliable OTA measurements, basic understanding of OTA testing principles is essential.

This paper first defines the antenna parameters to establish a common understanding for further discussion. Then, OTA losses, applicable OTA measurement setup, and the required calibration routines are discussed

II. ANTENNA PARAMETERS

A set of antenna parameters is used to describe the performance of an antenna and the impact the antenna will have in a larger system. Antennas can be categorized into active and passive antennas. Passive antennas do not feature any active components and act as baseline for typical antenna parameter characterization. Passive antennas are reciprocal, thus any discussion of radiation parameters are also valid for receiving signals. Active antennas on the other hand are radiating elements combined with some active components which characteristics can only be described as a combined system. As a result, reciprocity is broken and the determined characteristics can only be defined for the combination of the (passive) radiating part and active components.

For discussion of important antenna parameters, first a passive antenna transmitting a signal is considered. The signal is fed over a transmission line to the antenna. As part of a system, a certain power P_M is matched to the transmission line. Depending on the frequency dependent matching of the antenna, some energy is reflected back while the antenna accepts the remaining power P_{in} . The matching coefficient of the antenna is therefore depending on the system and is

expressed as reflection coefficient Γ or voltage standing wave ratio (VSWR):

$$VSWR = \frac{|V_{max}|}{|V_{min}|} = \frac{1 + |\Gamma|}{1 - |\Gamma|} \geq 1, \quad |\Gamma| \leq 1$$

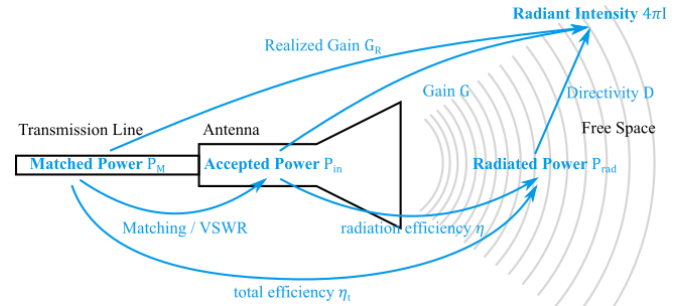


Figure 1: Passive antenna power, gain and directivity flow chart

Radiated Power

The radiated power P_{rad} is the accepted power P_{in} , reduced by any internal losses of the antenna, e.g. resistance losses. The ratio of radiated to accepted power is the antenna radiation efficiency η . The total efficiency η_t also considers the matching:

$$\eta = \frac{P_{rad}}{P_{in}} \leq 1, \quad \eta_t = \frac{P_{rad}}{P_M} \leq 1, \quad \eta_t \leq \eta$$

Having established the ratio of power available to the antenna to the power radiated by the antenna, no particular direction of radiation has yet been discussed. The radiated power is simply the integration of radiant intensity I in all directions:

$$P_{rad} = \int_{\phi=0}^{2\pi} \int_{\theta=0}^{\pi} I(\theta, \phi) \cdot \sin \theta \, d\theta \, d\phi$$

Directivity

Most antenna parameters are based on an ideal, theoretical isotropic radiator that has a constant radiant intensity in all directions. In reality, the existence of such a radiator is not possible. Consequently, every real antenna features some directivity of radiation. The antenna directivity is the ratio of the radiant intensity for a given direction to the radiant intensity that would be produced by an isotropic radiator with the same power P_{rad} .

$$D(\theta, \phi) = \frac{I(\theta, \phi)}{P_{rad}/4\pi}$$

If no direction is given, direction of maximum radiant intensity is implied:

$$D = \max_{\theta, \phi} D(\theta, \phi)$$

The directivity does not take any losses into account and therefore solely describes the relative variation of power distribution into different directions. If the antenna has higher radiation intensity in one given direction, some other

directions has a lower radiation intensity than the spatial average. The directivity is usually expressed in decibel relative to an isotropic radiator with directivity of 1:

$$D_{dBi} = 10 \cdot \log_{10}(D)$$

Antenna Gain

The gain is the ratio of the radiant intensity for a given direction to the radiant intensity that would be produced by a lossless, isotropic radiator with the same power P_{in} . It therefore combines directivity and efficiency:

$$G(\theta, \phi) = \frac{I(\theta, \phi)}{P_{in}/4\pi}, \quad G = \max_{\theta, \phi} G(\theta, \phi)$$

$$G_{dBi} = 10 \cdot \log_{10} G$$

$$G = \eta \cdot D$$

Instead of the radiation efficiency η , respectively the accepted power P_{in} , the total efficiency, respectively the available power P_M can be used to determine gain. This is the system dependent *realized gain* of an antenna:

$$G_R = \frac{I(\theta, \phi)}{P_M/4\pi}, \quad G_R = \eta_t \cdot D$$

Effective Isotropic Radiated Power

Directivity, gain and realized gain are all defined as power ratios. When it is required to express an absolute power value, the effective isotropic radiated power (EIRP) is used:

$$EIRP = P_{in} \cdot G$$

The EIRP is the power an ideal isotropic radiator requires as input power to achieve the same power density in the given direction.

Radiation Pattern

The radiation pattern represents the spatial distribution of a quantity that characterizes the electromagnetic field generated by an antenna. For reciprocal antennas the transmit and receive patterns are identical. The antenna pattern can be expressed as 3D plot, as 2D pattern cuts or as mathematical function. Directivity, gain or EIRP are often used for radiation pattern representation.

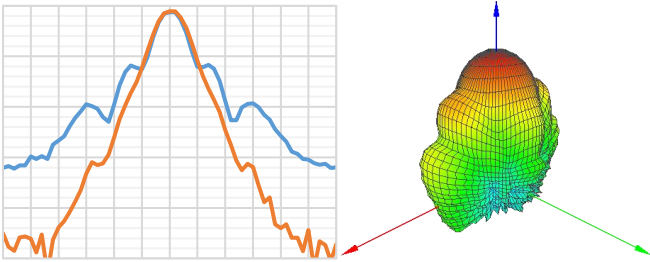


Figure 2: 2D and 3D radiation pattern

Half Power Beam Width

The half power beam width (HPBW) describes the range of angles in azimuth or elevation with at least $-3dB$ of the beam peak power.

Polarization

Until now, only the transmitter scenario was considered. As passive antennas are reciprocal, for every antenna that creates a certain radiation intensity I from a given power P_{in} , it is assumed that it also provides the same power level P_{in} when receiving a radiant intensity I . However, each field and field change caused by electromagnetic waves has a defined direction vector of the field components. Only when the E-plane of the antenna is aligned with the E-field vector of the wave, full energy is received. This direction is expressed as the polarization of the wave. An antenna's polarization is defined as the polarization of the wave transmitted by the antenna. For exactly the same polarization of an impinging

wave, the antenna is in co-polarization. Possible polarization types are for example linear or circular, with an elliptical polarization being the generalization of those. Arbitrarily polarized waves can be constructed from two orthogonal linear polarized waves with certain amplitude and phase offset as shown in Figure 3. If the antenna is not co-polarized with the wave to be received, a polarization mismatch will reduce the received power. In order to receive full power for arbitrary or unknown polarizations, dual polarized probe antennas with two orthogonal polarizations can be used.

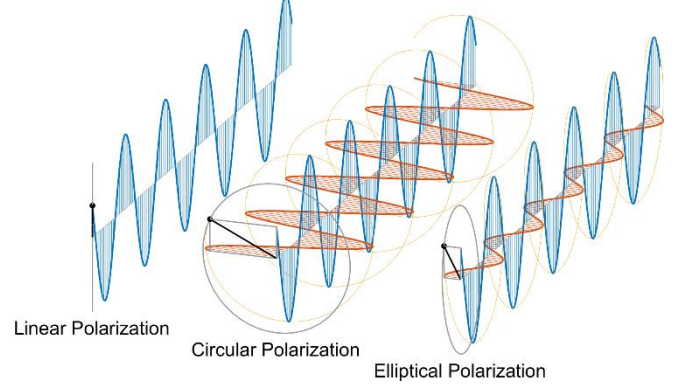


Figure 3: Polarized waves and orthogonal polarization components

III. NEAR FIELD AND FAR FIELD

All antenna parameters are defined in the far field (FF) region. Per Institute of Electrical and Electronics Engineers (IEEE) definition, the FF is the region where the field of the antenna is essentially independent of the distance from a point in the antenna region. In other words, in FF, free space and plane waves are assumed. To achieve free space characteristics, the line of sight (LOS) including the first Fresnel ellipsoid between the antenna under test (AUT) and probe antenna must be free of obstacles. Another important characteristic of free space is the absence of any reflection. Ideally, antenna measurements should be conducted in infinitely large rooms, which is not possible in reality.

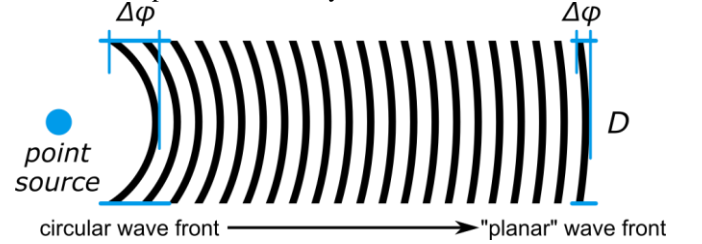


Figure 4: Scheme of wave front geometry

Depending on the device size D and frequency f , wave fronts can be assumed as almost planar at measurement distances greater than r_{FF} . For electrically large antennas, the Fraunhofer distance $r = 2D^2/\lambda$ is used as minimum FF distance. This distance ensures negligible amplitude difference over the surface of size D with a phase deviation of up to 22.5° .

Typically, the required FF distance is calculated based on the DUT size. For measurement chambers however, the measurement distance is fixed by the setup, and therefore a quit zone (QZ) is defined. The QZ is the region in a chamber in which FF conditions can be assumed. In an ideal environment, the QZ equals the calculated maximum device size D following the Fraunhofer equation with the given measurement distance and frequency. However, the advertised size of a QZ is strongly dependent on the QZ quality, e.g. caused by reflections. A large QZ with a amplitude difference of 2 dB and phase difference of 45° is

much easier to achieve than a QZ with a amplitude difference of 0.5 dB and 22.5° phase offset, for example.

IV. OTA LOSSES

The loss of signal power over the air makes up the majority in typical OTA test systems. The free space path loss (FSPL) is defined as:

$$FSPL_{dB} = 20 \cdot \log_{10}(d) + 20 \cdot \log_{10}(f) - 147.55$$

d is the distance between the antennas in meters, f is the frequency in Hz, and $d \gg c/f$ must hold.

The calculation of FSPL assumes isotropic radiator as transmit- and receive antennas. Since the antenna gain is also relative to an isotropic radiator, the actual OTA loss can easily be calculated using FSPL and antenna gain in dB and dBi, respectively.

Besides OTA loss, cable losses must also be considered. They are defined in decibel per length, thus the loss in dB increases linearly with distance. The FSPL in dB however increases logarithmic with distance. While at larger distance the FSPL increases slowly, it is much higher compared to cable losses at typical measurement distances. Still, also cables make up for considerable losses in the overall system, especially in mm-wave bands. A 1.5 meter test range at 30 GHz has a FSPL of 65.5 dB. 10 meter of cables with a loss of 3 dB/meter add additional 30 dB. The combined losses in an mm-wave OTA system require high dynamic range by the test & measurement equipment.

When conducting accurate measurements in OTA systems, alignment and positioning of DUT and measurement probe antenna are very important. In conducted measurements, movement and bending of cables can also cause slight variations in the scattering parameter. Misalignment of antennas or changes in the OTA measurement distance however will quickly cause high measurement uncertainty or wrong measurement results. Mechanical alignment of the setup is therefore of top importance for OTA testing.

V. OTA SYSTEMS



Figure 5: FAC at Rohde & Schwarz in Memmingen, Germany

Measurement chambers are essential for antenna characterization, but also advantageous or even required for other types of OTA measurements. A fully anechoic chamber (FAC) as classically used for antenna testing and characterization imitates an infinite room with the absence of any reflection or interfering signals. This is achieved by placing radio frequency (RF) absorbing material on any surface in the chamber and shielding the chamber itself so that external signals are heavily attenuated. The measurement distance is typically fixed due to the positioner setup and chamber size. From the used frequency, distance, chamber

geometry and absorber quality, a QZ is determined and evaluated.

Particularly with mm-wave antenna arrays, but also with electrically large devices in all frequency bands, the required FF distance is often too large to fit in an available FAC. If the AUT or DUT is larger than the QZ, FF conditions can no longer be assumed and the measurement results must be handled as NF data. This requires tight limits on the angular step size during measurement, accurate amplitude and phase information and transformation to FF in post processing.



Figure 6: Rohde & Schwarz ATS1800C CATR system for UE conformance testing

Alternatively, other types of chambers may be used to create a larger QZ with limited footprint. One example is the use of a compact antenna test range (CATR). CATRs use one or more RF reflectors to create a plane wave in front of the reflector at a distance smaller than the FF distance. The parabolic shape of the reflector transforms spherical waves to plane waves when the probe antenna is placed in the reflector's focal point.

As a passive, linear time invariant (LTI) system, this process is also reciprocal for transmission and reception. With the reduced test range and plane wave transformation also the path loss of CATR systems is significantly reduced compared to FACs with the same QZ size. To achieve a high quality quiet zone, the reflector must not deviate from the ideal parabolic shape and have a very low surface roughness. The upper frequency limit is defined by the surface roughness, as smaller wavelength are scattered by small bumps on the surface. The surface roughness should be less than $\lambda/100$ of the highest intended frequency. The lower frequency limit is mainly determined by the edge treatment of the reflector. A sharp edge causes significant amount of edge scattering that radiates into the quiet zone.

The QZ of a CATR system is roughly half the size of the reflector itself, but must be evaluated by measuring the amplitude and phase at different locations in the assumed QZ. The quality of the QZ is diminished by an amplitude taper caused by the feed antenna pattern, amplitude ripple due to imperfections and residual scattering, as well as phase taper and ripple.

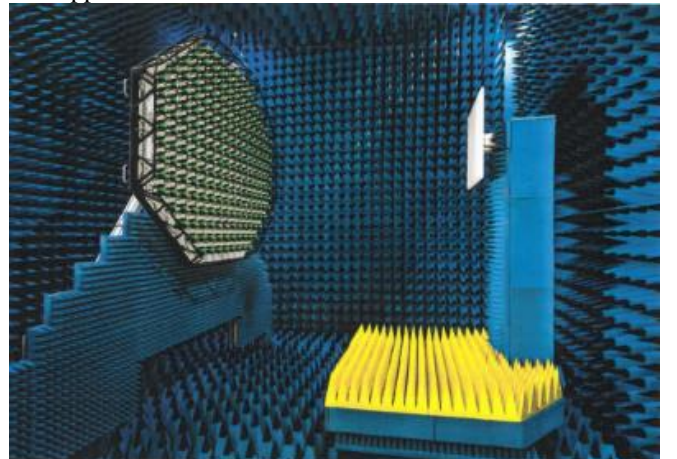


Figure 7: plane wave converter (PWC) at Rohde & Schwarz

In addition to CATR, other hardware can be used to transform spherical waves into plane waves. This can for example be achieved by using an antenna array with multiple antenna elements, each radiating a spherical wave with a certain amplitude and phase shift to create a plane wave in a QZ close to the antenna array. This approach is called plane wave conversion (PWC). Compared to a CATR system, bandwidth limitations are harder to overcome, but the footprint can be reduced even further, especially for frequencies where CATR reflectors feature serrated edges.

As already discussed, antennas only receive full power if they are co-polarized to the impinging wave. Therefore, regardless of the used measurement system, the probe antenna should always be dual polarized or implemented as a rotating single polarized probe, doubling the measurement time.

VI. SYSTEM CALIBRATION

In order to conduct accurate measurements, the system has to be calibrated diligently. As discussed already, the OTA link has a certain frequency dependent loss that is generally very high compared to conducted tests. Additionally, while a cable of a certain length has fixed attenuation, the OTA measurement distance can easily and inadvertently change, causing differences in attenuation and especially phase. Deviations occur even for small positioning errors or mechanical imperfections of the test fixture when rotating the DUT.

When calibrating an OTA system, where at least one interface is located in the air, a typical network analyzer port calibration or scattering parameter measurement of all components is not possible.

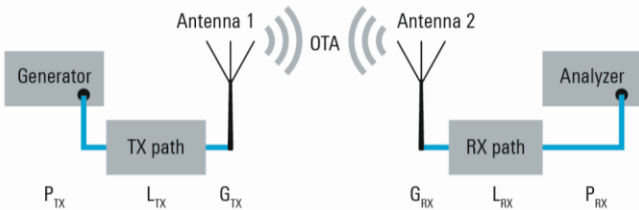


Figure 8: Generic OTA setup block diagram

The easiest process to determine the gain of any AUT is to compare the unknown antenna to a known reference antenna. For the following discussion it is assumed that the AUT is placed at “Antenna 1” in Figure 8. With the gain substitution technique a reference antenna with known gain G_{ref} is placed at the location where the AUT is to be placed. Generating a signal at the generator with power P_{TX} and receiving power P_{RX} with the analyzer, the overall system loss can be determined. For subsequently measurements of P_{RX} using the unknown AUT, the antennas realized gain G_{AUT} can be calculated:

$$L_{sys} = P_{TX,ref} + G_{ref} - P_{RX,ref}$$

$$G_{AUT} = P_{RX,AUT} + L_{sys} - P_{TX,AUT}$$

The known gain of the reference antenna is only valid for the peak gain direction of the antenna. The phase center of the antenna must be positioned in the rotation center of the positioning system, or if no positioning system is used, in a well-defined location which is constant for different measurement runs. This ensures, that for different AUTs and different measurement angles, the OTA distance between the AUT and probe antenna is always the same, thus the phase shift and FSPL OTA is constant for all measurements. This way, calibration also has to be done only in a single orientation. The reference antenna is fixed and the path loss

plus all other cable and component losses in the system for the two paths of the dual polarized probe are measured.

With the described procedure, the gain of all passive antennas can be determined straightforwardly. However, when characterizing active DUTs, the input power at the RF connected is of interest. To be able to determine the EIRP depending on input power, test internal power amplifier at different levels, or use an active device with internal signal processing and no RF port, L_{TX} must be determined individually. L_{TX} can be calibrated on the generator or in an automation software individually and removed from the overall system loss L_{sys} . Alternatively, $FSPL + G_{RX} + L_{RX}$ is determined after correcting the generator output by L_{TX} with a user defined frequency response correction using the gain substitution method as before.



Figure 9: User defined frequency response correction on R&S@SMW200A and R&S@FSW

When using a vector network analyzer (VNA), it makes also sense to perform a port and/or power calibration to the AUT feed, in order to be able to accurately measure the AUT matching and set a defined.

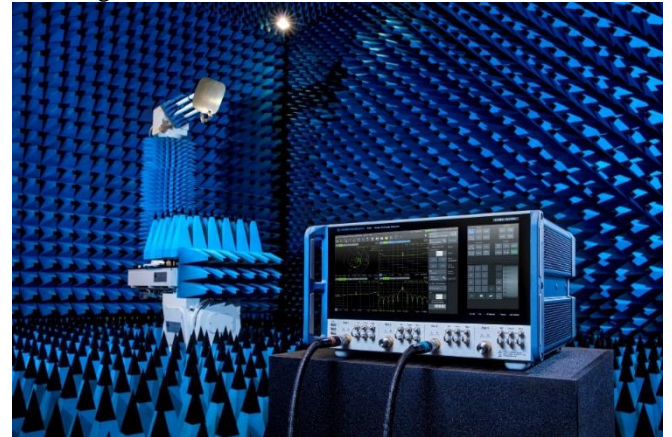


Figure 10: R&S@ZNA network analyzer for chamber calibration and antenna measurements

In general, either user correction features in the instrument, external correction of measurement values in the automation software, or a combination of both can be used to create a valid calibration of the OTA system. With all techniques, the user must thoroughly take note which part of the setup is corrected by which component in the measurement system (hardware and software).

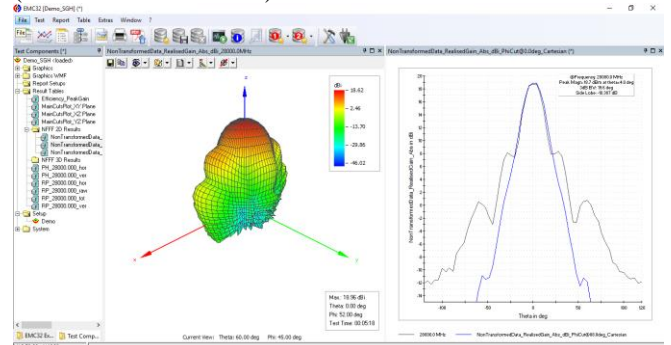


Figure 11: R&S@AMS32 antenna test & automation software

If no reference antenna is available, the gain of three unknown antennas can be determined using the three antenna method. Using a linear equation system, three unknowns (the antenna

gains) can be determined with three or more measurements. Here, typically the FSPL is estimated using the FSPL equation, and the conducted part of the setup is calibrated to the antenna feed points.

Alternatively, OTA power sensors can also be used to determine the power level at a point in the air without the use of a reference antenna.

VII. MEASUREMENT METHODOLOGY

The measurements to conduct of course heavily depend on the required information that is supposed to be gathered from the test. Different focuses of OTA testing might lead to different categories as follows: “classical antenna parameter characterization”, “RFIC and active antenna front end testing”, and “not antenna related OTA testing”.

As an additional case, regulatory requirements may also request certain OTA tests which then have to follow defined rules and are normally performed in dedicated conformance systems.

Classical antenna parameter characterization

When designing antennas or verifying the antenna individually from a DUT, the main focus for classical antenna parameters like matching, efficiency, directivity, gain, antenna pattern, etc. For this, an anechoic chamber or other type of antenna test chamber with a controlled environment, absorbers and high shielding effectiveness is mandatory. On top, an automated 3D positioning system is required. Only these systems allow reliable the measurement of 3D patterns to identify the directivity in all directions and therefore calculate peak directivity, gain and TRP. An automation software used to drive the chamber, measurement instruments, and calibration, is necessary.

RFIC and active antenna front end testing

When the focus shifts towards the active components of the DUT or an integrated antenna array, not all antenna parameters defined for passive antennas are relevant. Still, matching, directivity, TRP, and the antenna pattern can be of main interest. Especially for array antennas with beamforming capabilities, the pattern, HPBW, null location and depths are important features to be analyzed, requiring a 3D or 2D positioner. Compared to passive antennas, EIRP is more relevant than gain, as the integrated active components make it impossible to differentiate between the amplifier and antenna gain. EIRP values from different tests can only be compared if the input power or internal power setting of the DUT is noted.

Generally for testing, depending on the exact requirements, the same chambers as for classical antenna testing are required. In addition, climate control for fixed temperature or extreme condition testing may be required.

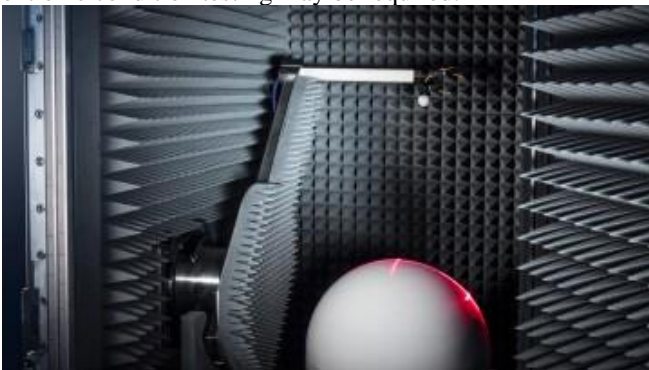


Figure 12:R&S@ATS-TEMP climate control bubble

Not antenna related OTA testing

What sounds like a contradiction might often times be the case: some component of the DUT shall be tested, but cannot be conducted due to a high integration level. If the antenna interface performance is already established or at least stable, the OTA link is treated a necessity for the actual test to be performed. Here, a small chamber or box with a fixed setup is sufficient. Shielding is required for not interfering with other test setups or environment signals, absorption helps to establish a fading-free link. High accuracy 3D positioning however is not required. Here, smaller FACs or even a CATR in rack form factor can be used for easy link setup, and also rapid prototyping in R&D.

Conformance Testing

Regulatory bodies as well as standardization groups define performance tests, mostly for user equipment, that deal with OTA testing. Typically, TRP and total isotropic sensitivity (TIS) have to be determined following a certain procedure as defined in the standard. Again, fully equipped and accurate antenna test chambers are required to fulfill the measurement uncertainty limits of those tests. The test procedures, the test site calibration, and verification are described in the respective standards.

VIII. CONCLUSION

Due to technological advancements integration levels in wireless devices are increasing, as well as the used frequencies. Both trends lead to an increased performance of OTA testing focusing either the antenna interface, or being a means to quantify the device performance. In both cases, awareness of the impact of OTA to the test setup is required. This is not only limited to wireless communications, also sat-com and testing as well as other tests in other fields have to be conducted OTA.

This paper summarized the most important parameters for antenna characterization to give engineers from different fields a quick and easy start to the world of OTA testing. Different calibration routines and measurement methodologies were addressed in this paper to give an overview of the variety of antenna testing and related OTA tests.

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